

OPTICAL PROTOCOLS FOR ADVANCED SPACECRAFT NETWORKS

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OVERVIEW

Most present day fiber optic networks are in fact extensions of copper wire networks. As a result, their speed is still limited by electronics even though optics is capable of running three orders of magnitude faster. Also, the fact that photons do not interact with one another (as electrons do) provide optical communication systems with some unique properties or new functionality that is not readily taken advantage of with conventional approaches. This paper describes some of the motivation for implementing network protocols in the optical domain, a few possible approaches including optical CDMA, and finally how this class of networks can extend the technology life cycle of the space station with increased performance and functionality.

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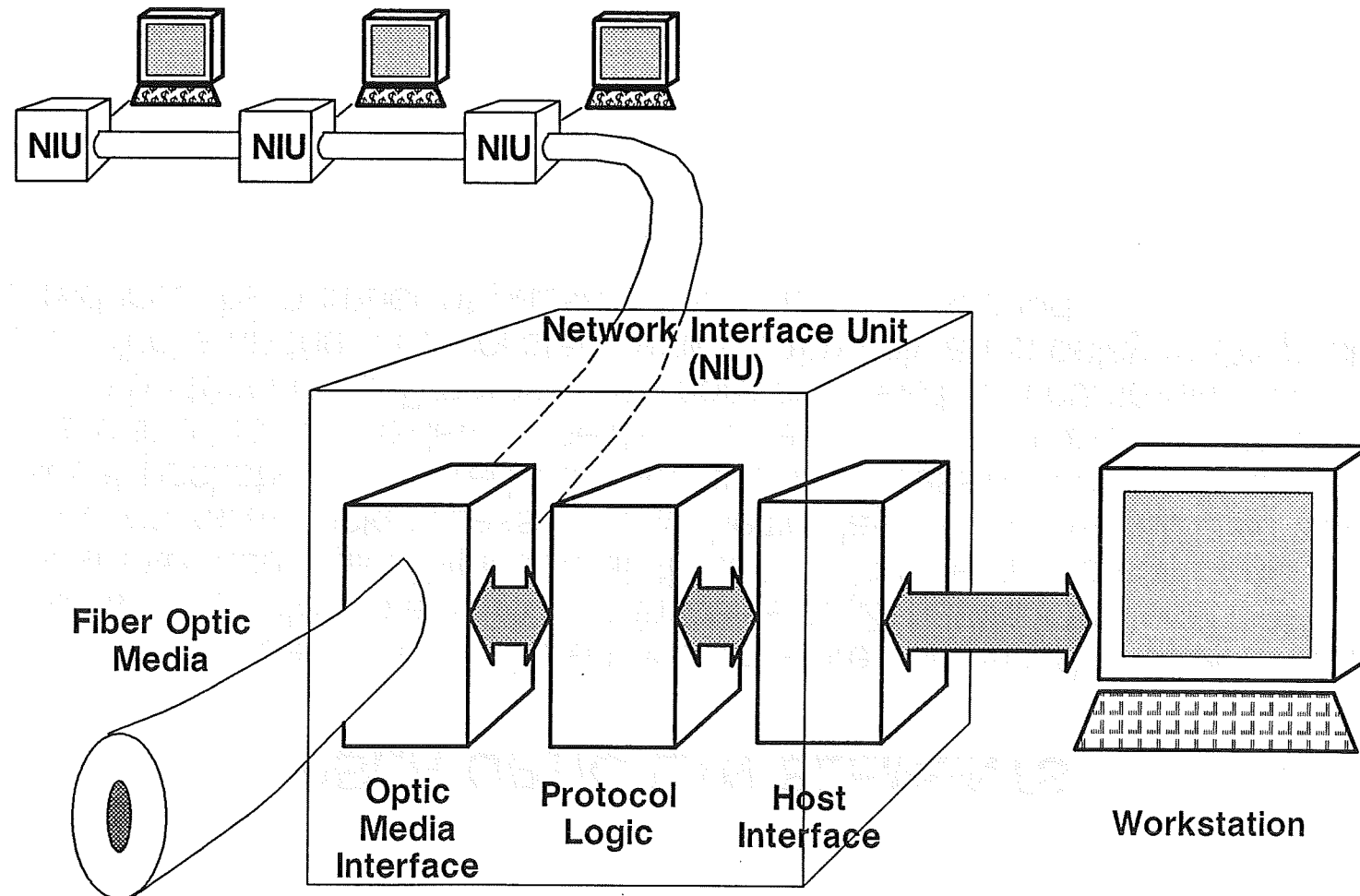
OVERVIEW

- Why optical?
- NASA needs
- Network bottleneck areas
- Possible solutions
 - components
 - architectures
- Spectral CDMA
- Technology availability

FIBER OPTIC LAN ELEMENTS

Contemporary fiber optic local area networks are comprised of three principal elements: (1) photon to electronic transceivers, (2) network protocol logic, and (3) host interface logic. Typically, all three employ electronic components. In most networks, all packets pass through the first layer to the second layer where non-local packets are filtered out. Additional processing occurs in the host interface and the host to determine the nature of the packet and to what service it should be forwarded. Progressively more overhead is accumulated as the packet climbs up the protocol stack which ultimately adds delay to the packet and reduces the number of packets transmitted by second.

FIBER OPTIC LAN ELEMENTS





BACKGROUND

By implementing the network protocols in the optical domain, the electronic bottleneck may be circumvented for many of the elementary functions (such as addressing) thereby increasing the packets that can be passed through a node up to and beyond 100Gbit/s. Other advantages include lower power consumption, non-blocking crossbar functionality, and higher security. To realize a fully photonic network, one must be able to implement boolean functions in the optical domain. A method based on spectral code division multiple access (CDMA) permits this style of implementation based on established optical processing techniques. Furthermore, it fully exploits the strengthes of optoelectronic components, and can utilize the full terahertz capacity of optical fibers.



BACKGROUND

- All optical local area network technology that provides:
 - very high aggregate speed ($>100\text{Gbit/s}$)
 - crossbar functionality (non-blocking)
 - high security
 - low powerneeded by next generation spacecraft instruments in early '00 (e.g., concurrent processors, optical telecom, etc)
- Optical protocol technology is based boolean functions implemented with coherent fiber optics and spatial spread spectrum techniques
- Exploits THz bandwidth capacity of single-mode optical fibers and non-linear behavior of optoelectronic devices
- Circumvents usual electronic and TDMA throughput bottlenecks



MOTIVATION

Many different types of applications are on the horizon that will demand higher speed networks including RISC-based instruments, high-rate IR/radar imagers, advanced parallel computers, and possibly optical telecom.

- RISC-based instruments
- High-rate IR/radar imagers
- Advanced parallel computers
- Possibly optical telecom



MOTIVATION

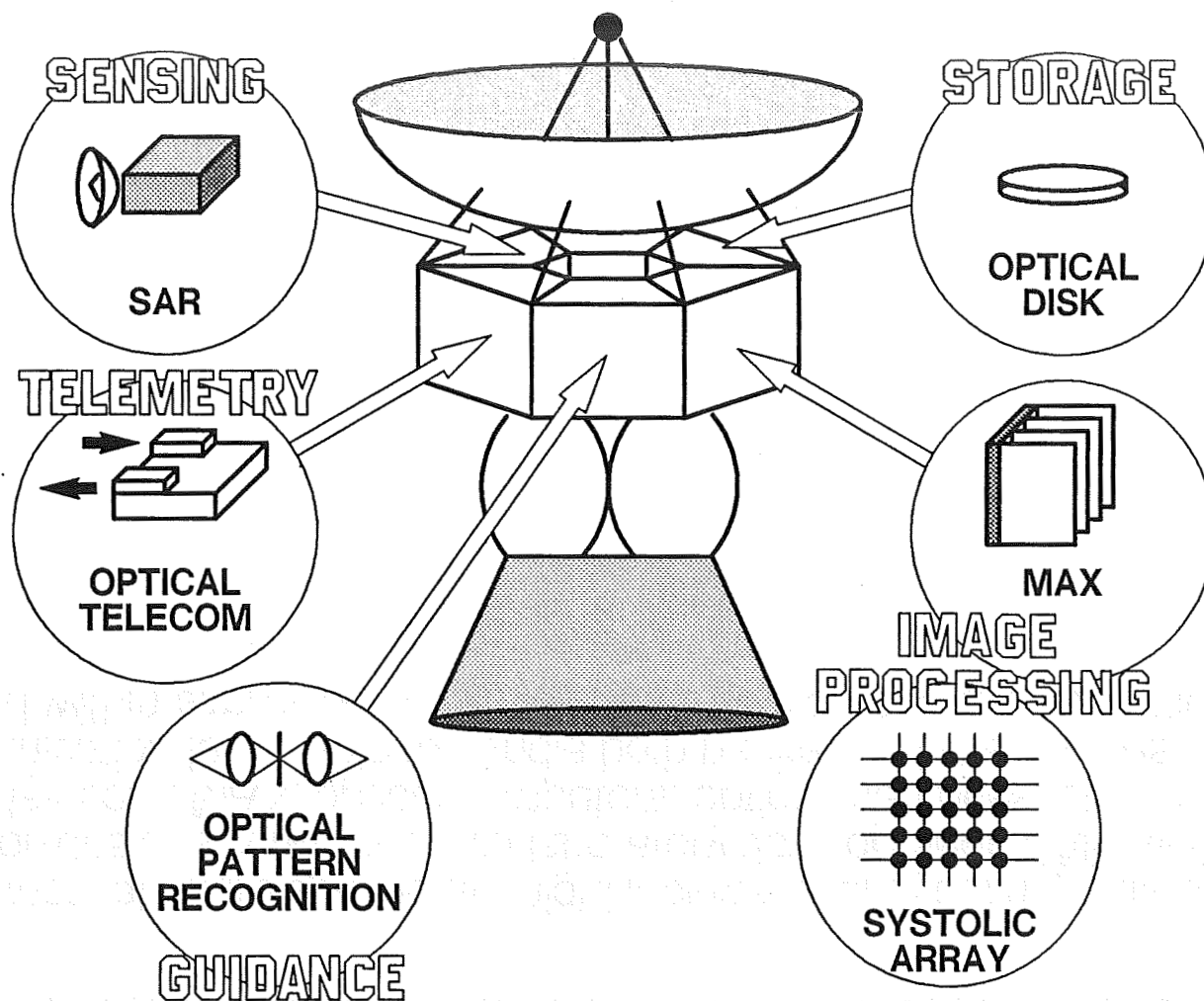
- Technology supports spacestation, future Earth orbiting satellites, and deep-space probes with high-bandwidth telemetry requirements, such as:
 - synthetic aperture radar (SAR)
 - optical processors
 - spaceborne supercomputers
 - optical memories
 - systolic array signal processors
- *Telescience* – future emphasis in preprocessing data during acquisition to reduce telemetry downlink bandwidth requirements
- Decentralization of resources, data bases, and computational power on a local and national level commensurate with GFlop/TFlop CPUs
- Spacecraft networks with reduced cable weight, low power, and increased security
- Provides communication fabric for HPCI and TouchStone TeraFlop massively parallel concurrent machines



HIGH DATA RATE SYSTEMS IN FUTURE SPACECRAFT

A hypothetical future spacecraft might include a variety of high rate instruments based on designs currently under laboratory development (SAR, systolic arrays, optical telecom, MAX, optical computers, optical memories, etc). A high speed communication fabric able to handle both packet and stream messages will be required within similar power envelopes that we have available today.

HIGH DATA RATE SYSTEMS IN FUTURE SPACECRAFT



- APPLICATIONS WILL REQUIRE A HIGH-SPEED (0.1-1 GBIT/S) DATA NETWORK ON-BOARD SPACECRAFT FOR BOTH STREAM AND PACKET TRAFFIC

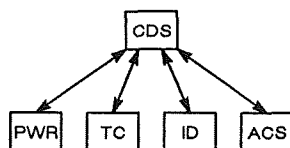


EVOLUTION OF UNMANNED SPACECRAFT DATA BUSES

The evolution of unmanned spacecraft data buses at JPL has spanned simple centralized communications topologies through parallel buses to (more recently) high speed networks. A system requirement has always been that the network offer deterministic packet transmission (bounded latency). As speeds and functionality increase, more instruments can be added with an increasingly larger range of services.

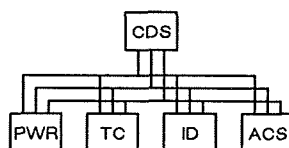
EVOLUTION OF UNMANNED SPACECRAFT DATA BUSES

SERIAL & CENTRALIZED



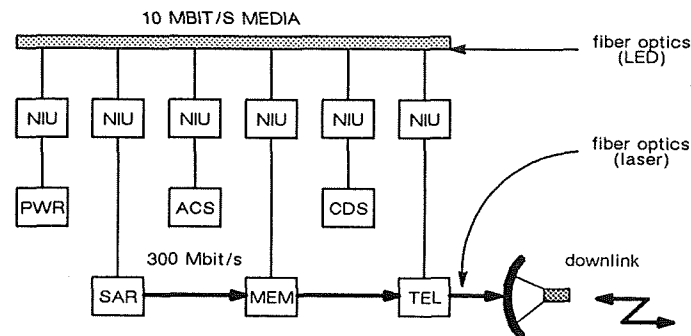
VIKING & VOYAGER
(1970-75)

PARALLEL BUS



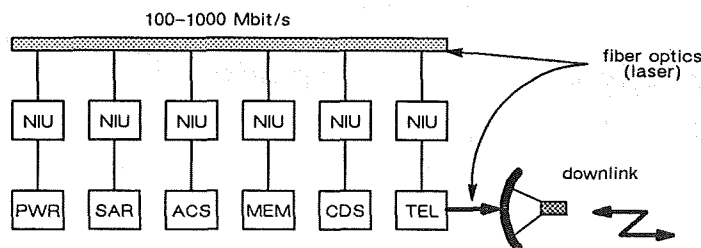
GALILEO
(1975-80)

LOW SPEED LAN



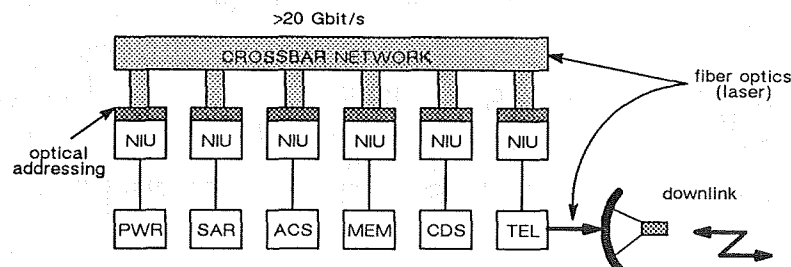
EOS 1
(1990-95)

HIGH SPEED LAN



EOS 2

ALL OPTIC LAN



MARS SAMPLE RETURN

Modular high-speed instruments, such as SAR, HIRIS, optical memories, systolic array and concurrent processors, will require distributed networks with multi-gigabit/sec speeds. An all-optic LAN would ideally overcome the NIU speed limit and provide connection style interfaces to real-time systems.



VIABILITY OF FDDI FOR SPACECRAFT

The 100 Mbit/s Fiber Distributed Data Interface (FDDI) has been under development by NASA, DoD, and many commercial companies. Based on a fiber optic dual token ring, the network offers standard multi-vendor interfaces, low EMI/RFI, multi-fault tolerance, deterministic packet transmission. Currently, the NIU logic is available in a small 3-IC chip set.



VIABILITY OF FDDI FOR SPACECRAFT

Advantages

- Speed matches next generation instrument technology *SAR, IR Imagers, signal processors*
- Fiber optic ready *all fiber attributes*
- Multi-fault tolerant *enhanced survivability*
- Deterministic *vital for stream traffic, control, heartbeat functions*

Disadvantages

- High power consumption *may limit to Earth orbiters*



OBJECTIVE

The main objective of the this research effort is to leapfrog current electronic-based network technology with an all-optic one that provides 100X improvement in speed, non-blocking crossbar functionality, and hybrid services (packet and stream). It also intends to demonstrate optical protocols with an existing space station DMS testbed, and identify technology availability.

- Develop DMS testbed for optical network
- Develop optical network architecture
- Develop testbed for optical network architecture
- Develop testbed for optical network architecture
- Develop testbed for optical network architecture

OBJECTIVE





OBJECTIVE

- Leapfrog conventional electronics-bound network technology with optics to achieve 100X improvement in capacity, reduced power, and integrated service functionality
- Demonstrate that electronic protocols can be implemented in the optical domain
- Develop DMS network migration paths



BENEFITS OF LANs IN SPACECRAFT

Networks offer increased speed, simpler wiring, and interchangeable modularity. All these factors enhance making the system easily reconfigurable—and even serviceable—in space.

- Increased speed
- Simpler wiring
- Interchangeable modularity
- Easy reconfiguration



BENEFITS OF LANs IN SPACECRAFT

- | | <i>Impact</i> |
|--|--|
| ● High-speed | <i>greater throughput</i> |
| ● Daisy chain wiring | <i>less required cable</i> |
| ● Time Division Multiple Access (TDMA) | <i>shared user cost</i> |
| ● Standard protocol and interface | <i>modular instruments,
increased testability,
off-the-shelf GSE</i> |
| ● Reconfigurable | <i>changes easily
accommodated</i> |



BENEFITS OF FIBER OPTICS IN SPACECRAFT

In addition to enormous bandwidth, fiber optics also provide enhancements in EMI/RFI immunity, ground loop isolation, no external emissions, and small size, weight and power consumption.

• High bandwidth

• Low loss

• EMI/RFI immunity

• Ground loop isolation

• No external emissions

• Small size, weight and power consumption

• High reliability

• Simple installation and maintenance

• High security

• Low cost

IN SPACECRAFT

RESEARCH OF JPL AND OTHERS



BENEFITS OF FIBER OPTICS IN SPACECRAFT

Impact

- Light weight
- Small size
- Low power
- No emissions (E/M)
- Immune to RFI, EMI, ground loops
- Very large bandwidth
- *greater payload*
- *smaller right-a-way*
- *smaller pwr plant*
- *relaxed routing,*
- *boom instruments*
- *relaxed routing,*
- *simplified integration*
- *supports future*
- *instruments*



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APPROACH

- Analyze present DMS baseline to establish network topology, protocol, and interface requirements
- Develop and demonstrate two-node optical testbed for stream and packet traffic
- Analyze optical protocol suite tradeoffs and compare with other approaches
- Identify DMS network upgrade paths
- Conduct interface demonstration with another DMS system

ELECTRONIC NETWORK BOTTLENECK AREAS



COMPONENT TECHNOLOGY LIMITS

The speed of state-of-the-art electronics and optoelectronic components currently is about 20GHz while fiber optic media provides three orders of magnitude more capacity (to 50THz). Tapping into this enormous bandwidth is simplified if the electron-based devices can be removed from the first few tiers of the network protocol stack.



COMPONENT TECHNOLOGY LIMITS

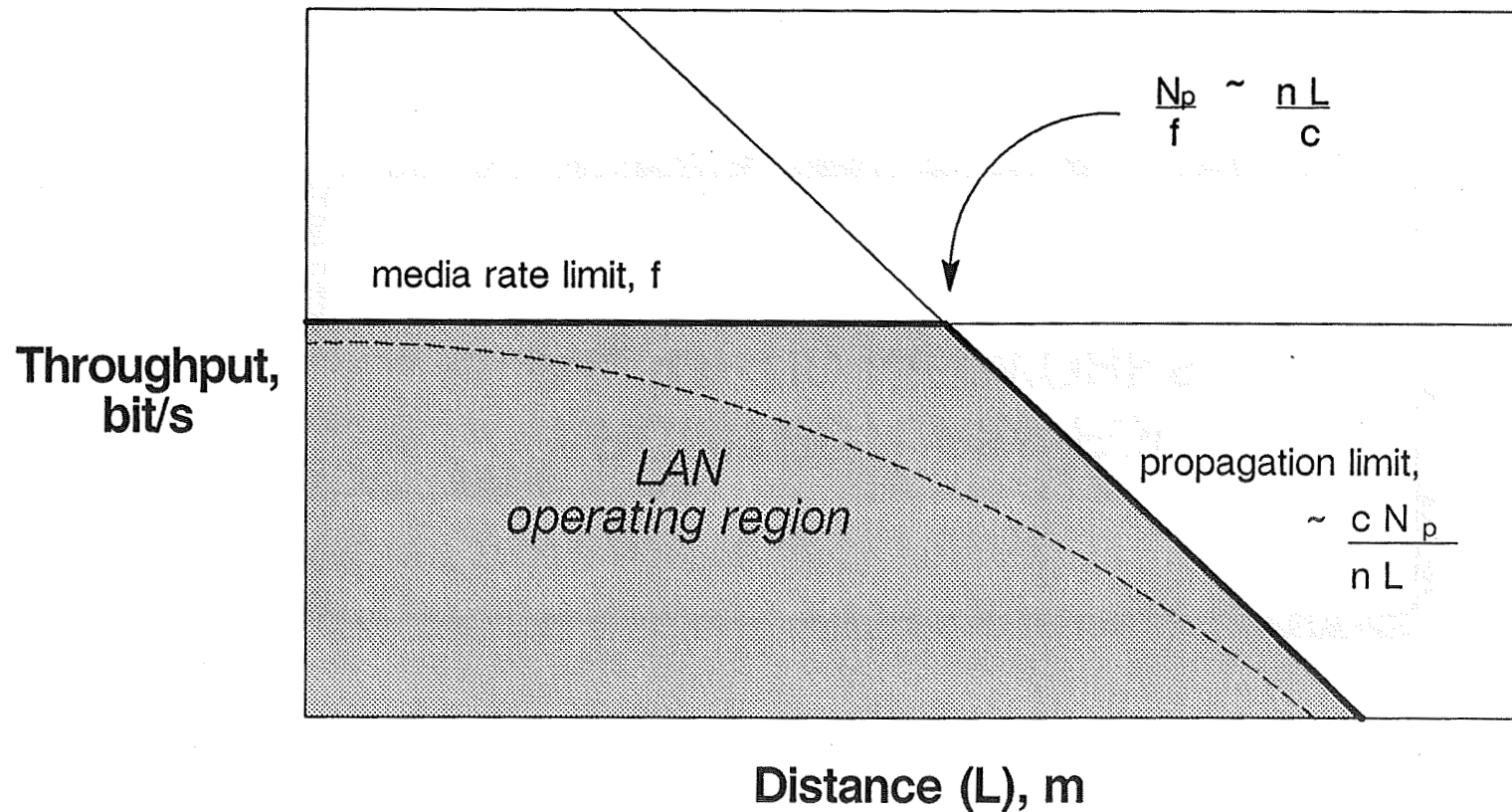
	<u>Now</u>	<u>Future</u>
● Electronics		
● MESFETs (GaAs)	15 Gb/s	35 GHz
● HEMT (GaAs @ 77°K)		100 GHz
● VLSI (GaAs/2K gates)	5 GHz	20GHz
● VLSI (Si/1K gates)	~1GHz	12GHz
● Optoelectronics		
● laser diodes sources (InGaAs/P)	16 Gb/s	45 GHz
● modulators (LiNb, MQW InGaAs)	20 GHz	>100 GHz
● photodetectors (InP/GaInAs, GaAs)	20-40 GHz	100 GHz
● Media (L=1Km)		
coax	300 MHz	
multi-mode fiber	3 GHz	
single-mode fiber	>200 GHz	>10THz
● Peripherals		
processors (RISC)	25MHz	>200MHz
memories (GaAs)	~1 GHz	>10GHz



FUNDAMENTAL TDMA PROTOCOL LIMITS

Conventional local area networks (of few km length) employ Time Division Multiple Access (TDMA) protocols to arbitrate fairly between users. Generally, these networks are limited by two mechanisms: one is the signalling limit on the channel imposed by the network interface components, and secondly, a protocol-dependent propagation delay limit that varies inversely to the length of the network. The latter comes about because TDMA protocols, whether it be ethernet or token rings, arbitrate fair use of the common channel by guaranteeing that each user (or node) will have an opportunity to talk during a given period. In effect, the bandwidth of the channel is distributed evenly among the users. A by-product of this is that a node must listen for a period equal to the propagation delay of the media between transmissions. Hence, if the packet size remains constant, the efficiency will decrease as the data rate increases. This suggests one reason why higher speed networks, such as FDDI or HIPPI, have defined larger packet sizes.

FUNDAMENTAL TDMA PROTOCOL LIMITS



Packet size must scale with bit rate to maintain high efficiency for "fair" protocols. Suggests WAN strategies for > 100 Gbit/s – terabit local networks?

ARCHITECTURES FOR ALL-OPTIC NETWORKS



SOME CANDIDATE ALL-PHOTONIC ARCHITECTURES

Two of the most prevalent all- or mostly- optic network systems being explored today are dense wavelength division multiplexing (WDM) and code division multiple access (CDMA). Both partition the optical spectrum into channels in order to circumvent the limited signalling rate of electronic components. With WDM, each channel operates on a separate wavelength. No provisions are made to implement protocols optically (this is typically done in a companion electronic network). With CDMA, the approach is slightly different in that all channels are encoded with a unique code that is spread over all wavelengths. Thus, each channel occupies all of the 10THz spectrum, but is non-interfering with the others since it is orthogonal (by design). The net effect with CDMA is that the network behaves as a non-blocking crossbar switch. Furthermore, the CDMA encoding method can be based on phase encryption of the multi-wavelength front, which preserves optical power and makes the method amenable to fourier optics implementation and the possibility of adding boolean functions.



SOME CANDIDATE ALL-PHOTONIC ARCHITECTURES

- Very dense WDM
- Fiber Optic Code Division Multiple Access (FO-CDMA)



POTENTIAL OPTICAL NETWORK PROTOCOLS

A few of the more widely known protocol functions that must be implemented by a network are regeneration, addressing, arbitration, error detection and correction, flow control, routing, and authentication. In an all-optical network, the order of some of these may in fact be altered due to the unusual properties of the spectral CDMA. For example, addressing and routing may be conducted before regeneration.



POTENTIAL OPTICAL NETWORK PROTOCOLS

- Regeneration *
- Flow Control *
- Addressing
- Arbitration
- Routing (and Address Translation)
- Encryption
- Error Detection/Correction
- Authentication

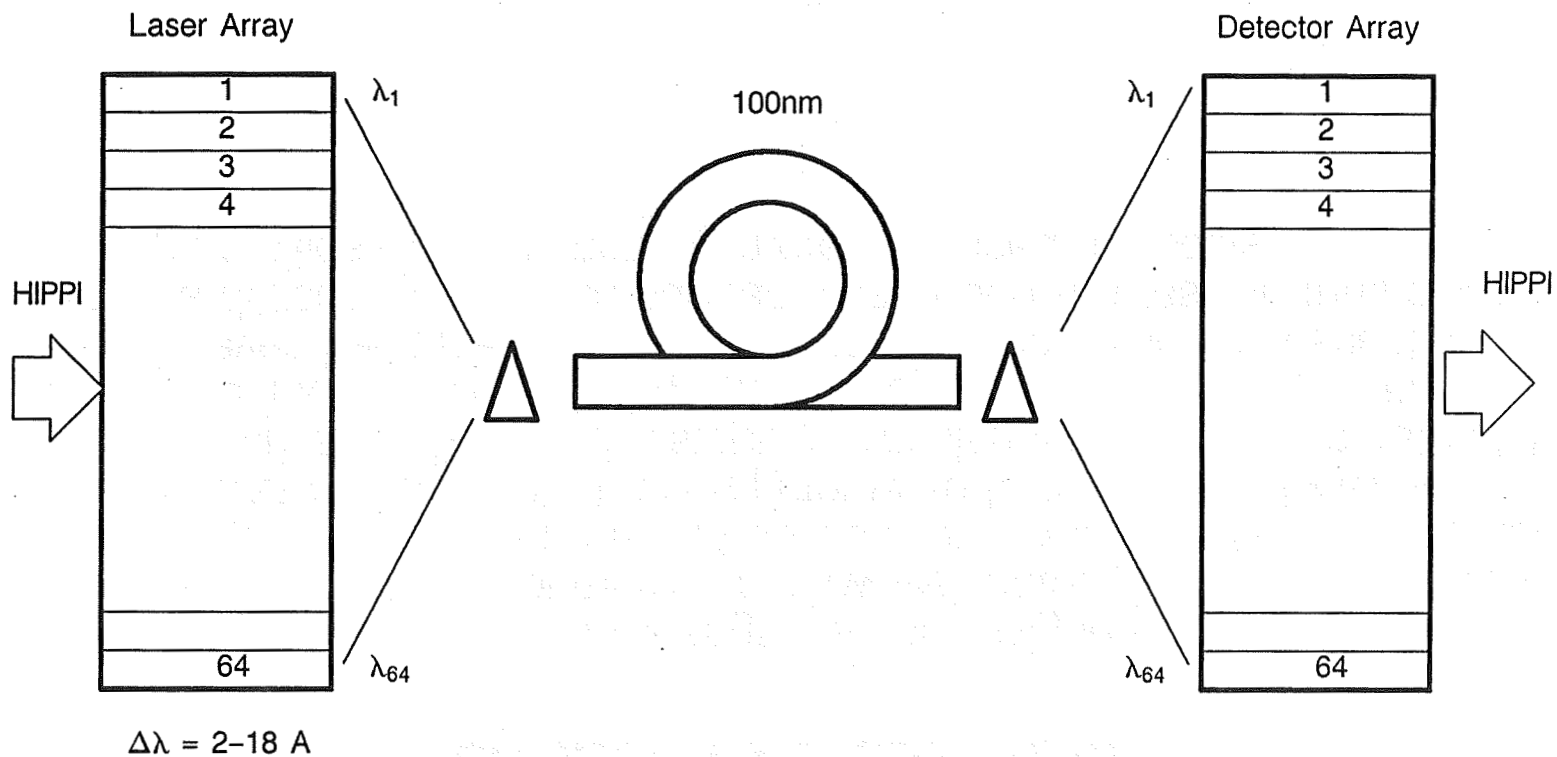
* more difficult to implement optically



DENSELY PACKED WDM

In dense WDM, one channel wavelength can be assigned to one service, e.g., voice, video, etc. Sixty-four or more of such wavelengths can be closely spaced and passed over a single-mode optical fiber at 1.55 μ m. However, another method is to assign each bit of a computer word to an individual wavelength. Assuming each laser diode in the stepped wavelength array can operate at 1 Gbit/s, such a link could conceivably operate beyond 64 Gbit/s (for a 64 element array). However, because each laser operates incoherently with respect to the others, it is difficult to sum and subtract bits in boolean fashion thus closing many opportunities for implementing more advanced protocols.

DENSELY PACKED WDM





CDMA FOR CELLULAR TELEPHONE

Although spread spectrum communications has been used primarily for military communications for the last few decades, CDMA is now being used for commercial deployment of cellular telephone networks to squeeze more capacity out of the existing RF spectrum and to allow more rapid reconfiguration of the system and growth.

PacTel Cellular Takes a Gamble on Technology

■ Telecommunications:

Mobile phone companies are adopting new systems. The Southland's biggest carrier has decided to go its own way.

By DEAN TAKAHASHI
TIMES STAFF WRITER

Jeffrey R. Hultman, president and chief executive of PacTel Cellular, likes to tell his employees that they are pioneers in a "100-year business."

Taking a long-term view keeps a decision such as which of two competing cellular phone technologies to adopt from seeming quite so daunting, he says. Even so, Hultman and other cellular industry executives are grappling with the biggest technological transition in the industry's brief history.

The change involves modernizing the nation's cellular networks with second-generation digital technology that will allow cellular companies to squeeze calls onto an already cramped wave band.

For PacTel Cellular, the nation's second-largest cellular phone company, the change comes at a crucial time. In Los Angeles, the Irvine-based company's largest market, the carrier that converts to digital first could capture the lion's share of subscrib-

CELLULAR: PacTel Decides to Go Its

Continued from D1

and PacTel has a reputation for doing that."

Hultman said he was skeptical when officials from Qualcomm Inc., a San Diego start-up, approached him late last year and told him their digital technology—known as code division multiple access, or CDMA—would allow PacTel to squeeze 20 times more callers onto the existing network.

After all, just a few weeks earlier and at Hultman's recommendation, the Cellular Telecommunications Industry Assn. voted unanimously to adopt a digital technology called time division multiple access, or TDMA, ending a two-year dispute over industry standards. Because it emerged so late, CDMA was not considered.

TDMA extracts three to seven times more capacity from the existing analog system by slicing a frequency into a number of time slots. The transmitter bursts a signal for a call for a given period of time and then alternates to another call, dropping the first one for a split-second. The caller can't notice the gaps between the call signals because they are so short. In effect, several calls are handled simultaneously on the same frequency.

But CDMA systems, first developed by the military to protect radio communications, spread a number of call signals across the available frequency spectrum simultaneously and assign a unique binary code to each signal. The signals are sorted from the bus

next year. He cautions, however, that any further disputes over standards could delay industry growth and raise the cost of digital cellular equipment.

Some industry observers say PacTel and others who support CDMA are hurting the industry by not being team players and endorsing the industry standard.

"What is disturbing is that certain companies [that support CDMA] are so willing to pursue a panacea that isn't proven and wasn't part of the testing process that arrived at a standard," said Eric Lissakers, director of planning and development for Ericsson Radio Systems, a Richardson, Tex., cellular phone manufacturer. "They are looking at a rainbow instead of the planned evolution of a standard."

Mark Buford, a spokesman for Northern Telecom Inc., a Canadian telecommunications manufacturer, said his company has endorsed TDMA but continues to explore CDMA as an alternative. He said any changes could result in higher development costs and a delay in the conversion to digital.

For its part, the Federal Communications Commission ruled in 1987 that carriers do not have to follow a particular standard, so the choice between technologies could be made on a market-by-market basis.

But PacTel's Hultman argues that the advantages of CDMA technology are too big to ignore.

northern Orange County.

Today, PacTel has more than 470 cell sites covering 10,000 square miles in five Southland counties. Of the company's 448,000 subscribers, about 170,000 are in Los Angeles, estimates Herschel Shostack, a cellular market researcher in Silver Spring, Md. About 40% of PacTel's Southern California customers are in Orange County.

The company's growth in Southern California reflects the enormous popularity of cellular phones in the land of car-crazy commuters and clogged freeways. And growth has been brisk in PacTel's other California cellular markets: San Francisco, San Diego and San Jose. PacTel provides cellular service in more than 20 cities, including Atlanta.

With 30 million potential subscribers in its coverage areas, PacTel Cellular is second only to McCaw Cellular Communications of Kirkland, Wash.

Nationwide, the number of cellular subscribers is expected to rocket from 3.5 million last year to at least 18 million by 1995, Shostack estimates. About 10% of the nation's cellular phone subscribers are in greater Los Angeles, the nation's second-largest market after New York City.

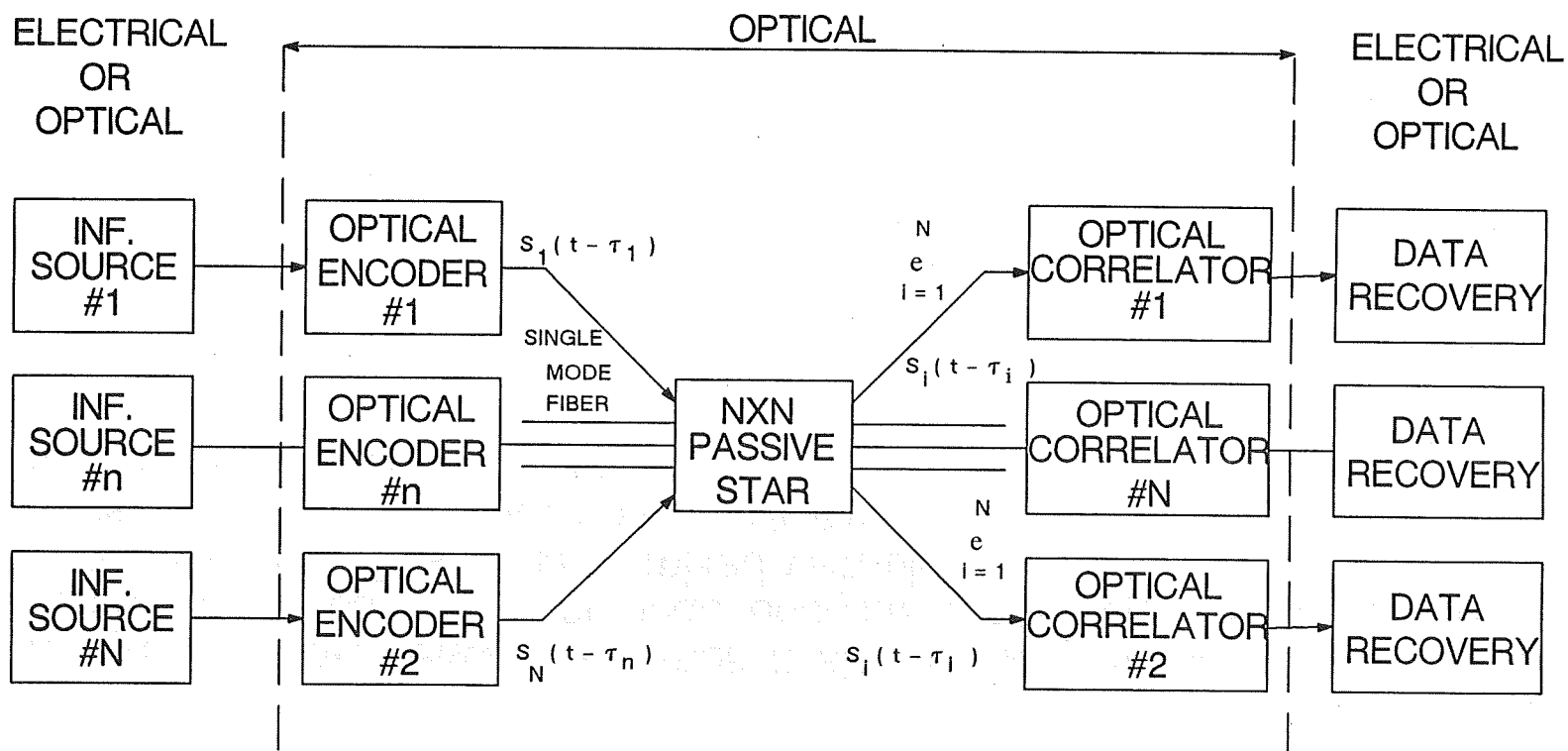
PacTel has grown to more than 1,300 employees, including 535 in Orange County, and plans to add 300 more employees by year-end. Three weeks ago, it began moving its headquarters staff to new quarters in Irvine.



FIBER OPTIC CDMA

The basic CDMA network assumes a star topology (although this can be altered) where each user or node encrypts a message using his specific orthogonal code. This signal is mixed with all others and re-distributed to all nodes on the network. Each network receiver then applies a key to filter out all other channels except the one of interest.

FIBER OPTIC CDMA



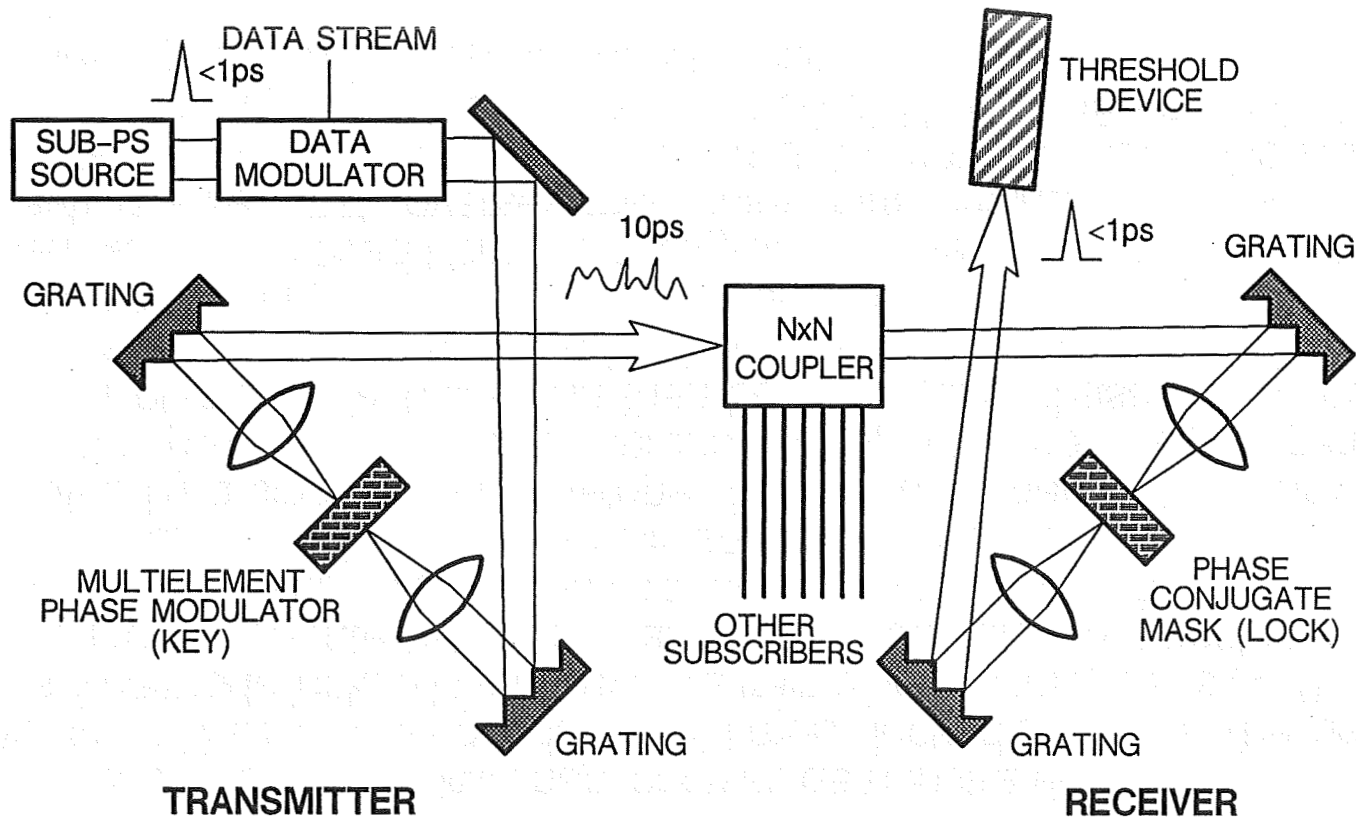
Fiber optic code division multiple access (FO-CDMA) implemented in a STAR configuration (c.f., Salehi, 1987).



FIBER OPTIC CDMA

The first basic spectral CDMA network was demonstrated by Salehi, Brackett, and Weiner at Bellcore using a visible light mode locked dye laser. The idea is as follows. The mode locked laser delivers a train of very short pulses ($<100\text{fs}$) at a very high repetition rate ($>1\text{GHz}$) to an optical modulator. The host then drives the modulator to extinguish or pass bits of this train. A simple fourier analysis of this bit stream would suggest an RF spectrum resembling a comb function modulated by a sinc^2 power envelope. This signal is then passed through an optical grating and lens to spatially spread each spectral line across a spatial light modulator element. Each line can then be individually phase modulated, 0 or 180 degrees, using the prescribed orthogonal code set and then recombined with another grating/lens assembly and sent out to the network. This specific channel can be retrieved from the background noise of the the other channels by creating a key that reverses the phase shifts originally introduced at the transmitter. All other channels are rejected. JPL is now extending this system to the minimum dispersion wavelength of optical fiber ($1.55\mu\text{m}$), and building higher level protocols on top of this foundation.

FIBER OPTIC CDMA



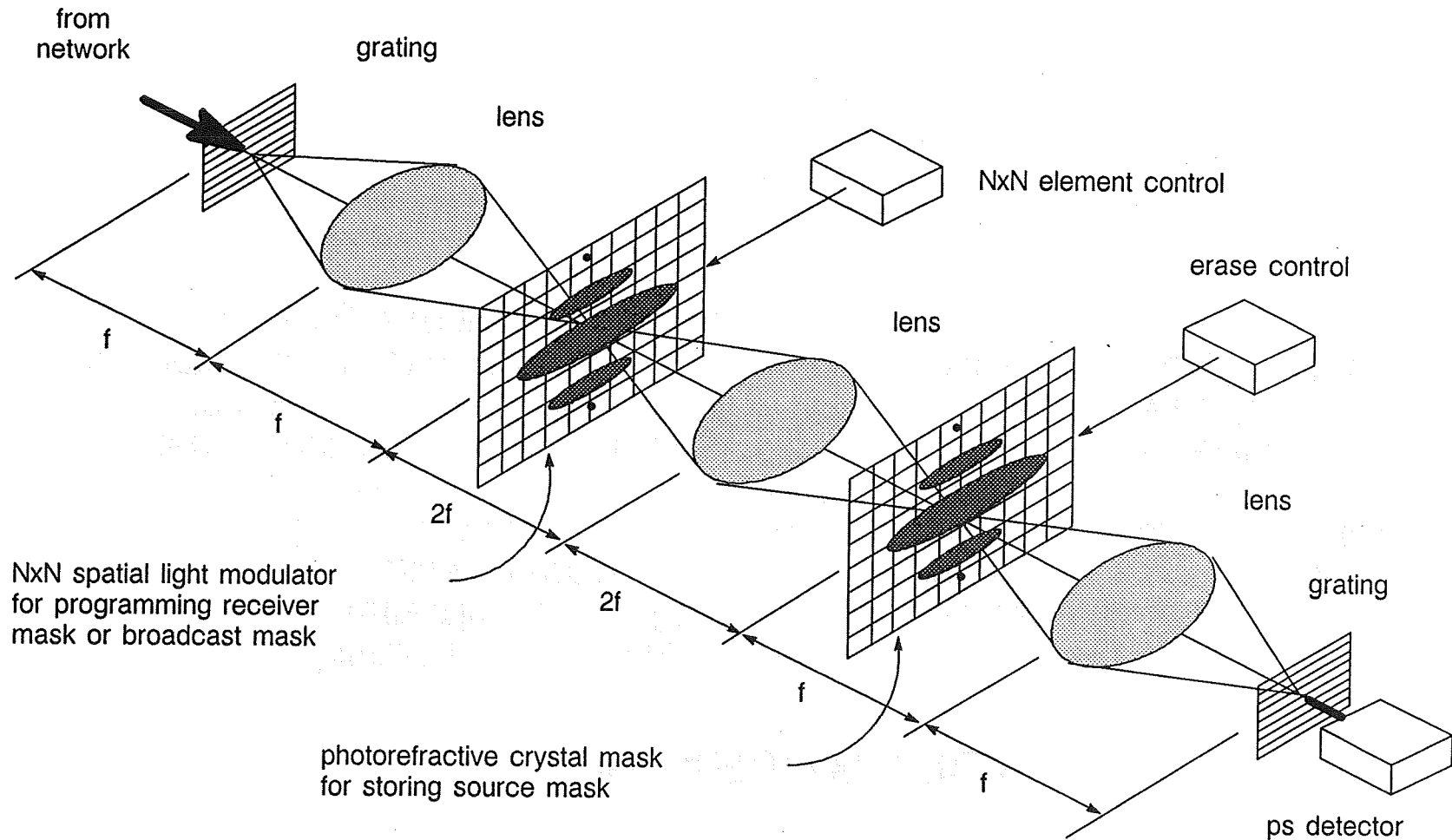
Fiber optic code division multiple access (FO-CDMA) network uses frequency spreading rather than temporal spreading (c.f., Salehi, 1988).



OPTICAL ARBITRATION

Pure optical arbitration can be implemented in a receiving station using a secondary photorefractive mask. The first SLM mask is used to program the local station's address or a network broadcast address. The second mask is a photorefractive crystal programmed by the first source node able to write to it. Data flows from the source node to the destination node after the second mask is written. Other stations are blocked. Once complete, the receiver station erases the second mask allowing other source nodes to write to it. This approach has an advantage over hybrid optical/electronic approaches in that less handshaking is required between the nodes.

OPTICAL ARBITRATION



$N \times N$ spatial light modulator
for programming receiver
mask or broadcast mask

photorefractive crystal mask
for storing source mask



OPTICAL SYSTEM POWER BUDGET

All the losses in any optical network must not exceed the difference between the transmitter power output and the receiver sensitivity. Since the spectral CDMA uses a mode locked laser, this power level can be quite high. However, it also has additional losses over the typical optical link, such as spatial modulator losses, coding losses, grating losses, and polarization correction losses. When all added up, these losses fall between the power budget for a coherent and incoherent transmission system. The system shown would support 32 users at 1 Gbit/s using a coherent detector.



OPTICAL SYSTEM POWER BUDGET

	dBm	dBm
Source ($P_t=1W$)	+30	
Receiver ($P_r=2\mu W$: non-coherent)	-25	55dB
Receiver ($P_r=20nW$: coherent)	-45	75dB
Optical Components:		
gratings (4 x 85%)	-3	
fiber coupling loss (3 x 1)	-3	
fiber absorption loss (100m)	-1	
star coupler division loss (32x32)	-15	
SLM absorption loss (2 x 10%)	-20	✓
Modulation Effects:		
bandlimiting effects	-10	✓
CDMA channel interference ($n=10$)	-10	
TOTAL SYSTEM LOSS:		62dB

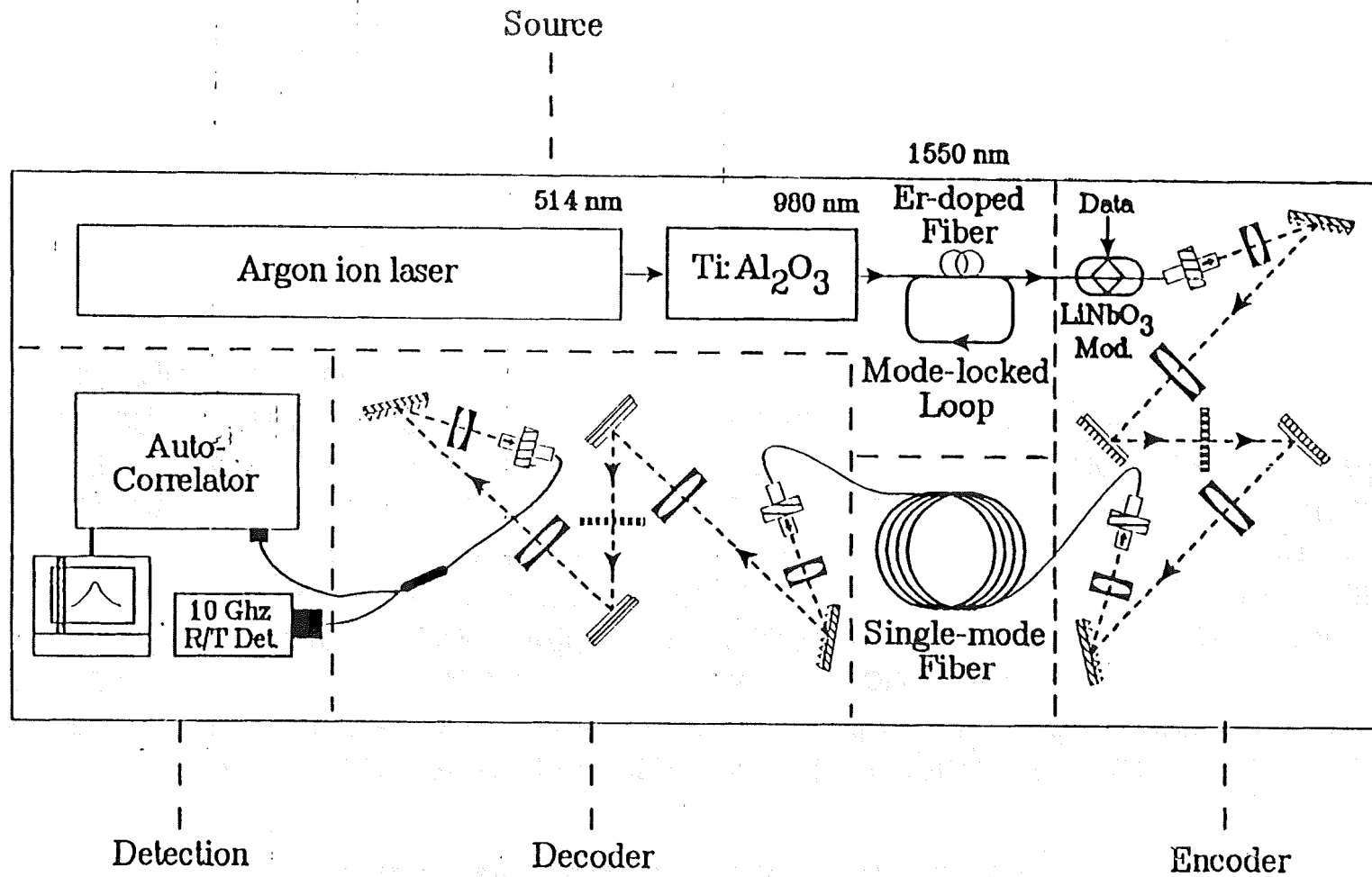
CONCLUSION: Sufficient power budget is available for femtosecond CDMA, especially if optical fiber amplification is used.



LABORATORY EXPERIMENT

The laboratory experiment constructed at JPL employs an Argon pumped Ti:sapphire laser that delivers 980nm/20W to an erbium fiber ring cavity that is in turn excited to lase and passively mode lock at 1.55um/50MHz. Pulses as short as 700-fs have been obtained with this system and further reduction in pulse width (which translates into more channels) is possible with additional fiber compression stages. In the future, the bulky Argon pump laser could be replaced by a small cm-size semiconductor laser operating at 980nm. Further integration should permit the laser, its mode locker cavity, the data channel modulator, gratings, lens, and spatial light modulators to all be put onto the same integrated optic chip.

Optical Protocols Lab. Set-up





TECHNOLOGY AVAILABILITY

Since spectral CDMA is only in its earliest stages of development leading toward a concept demonstration, many evolutionary steps are envisioned before an actual commercial system could be built. However, even at this early stage, some trends may be identified that would maximize technology insertion potential by stages into a large system such as space station. For example, in the near term the baseline design calls for 100 Mbit/s FDDI network. A natural (interim) second step that would preserve all the existing system interfaces would be to pack more FDDI channels into the same optical fiber using dense WDM techniques, which is expected to mature earlier than CDMA. Many of the gratings, micro lenses, and couplers used in WDM would also be needed in the spectral CDMA, and so, such a step would allow early returns of R&D investment in more fundamental devices needed for WDM and CDMA systems. A final step would be to migrate to full spectral CDMA which would allow individual interfaces to be elevated to beyond 100 Gbit/s and new forms of services to be added.

TECHNOLOGY AVAILABILITY

- **BASELINE CAPABILITY (NOW)**
 - NET: dual-redundant (Class A) 100 Mbit/s token ring (FDDI)
 - CABLE: multi-mode fiber optics
 - CONNECTORS: multi-mode tolerance components
 - TOPOLOGY: 38 concentrators x 8 ports = 304 users (ring)
 - SOURCE: LED or laser diode
- **INTERIM (FY'96)**
 - NET: multiple FDDI rings WDM-muxed onto single fiber (5Gbit/s)
 - CABLE: single-mode and multi-mode fiber optics
 - CONNECTORS: single-mode tolerance components
 - TOPOLOGY: multiple rings through patch panel
 - SOURCE: 16-64 element laser diode stepped λ array
- **LONG TERM (FY'01)**
 - NET: all-photonic CDMA crossbar (>100Gbit/s)
 - CABLE: single-mode dispersion flatten fiber optics
 - CONNECTORS: single-mode tolerance components
 - TOPOLOGY: multiple logical rings, star, or mesh
 - SOURCE: integrated optic mode-locked laser & modulator



BASELINE INTEGRATION

This effort will ultimately produce a two-node laboratory demonstration that will interface two forms of services (e.g., image streams and computer packet). It is planned to develop an interface to the DMS testbed at ARC to fully assess space station requirements and performance benchmarks with this new generation of network. Three basic groups of tests are planned, including functional system interface requirements, network performance, and mechanical interfaces. The effort also draws upon integrated optic component reserach development efforts at JPL and elsewhere.



BASELINE INTEGRATION

- Interface with ARC DMS testbed
- Functional assessment
- Performance assessment
 - NIU power consumption
 - optical power budget
 - protocol latency and speed
 - number of channels
 - error rate
- Mechanical interface assessment
 - size
 - weight
 - topology



NEW COMPONENTS REQUIRED

A variety of new components are required to fully realize such a system commercially. Some of these devices include coherent fiber optic media, couplers, star splitters, and modulators), mode locked lasers on a chip, fast (1Gbit/s) 1D spatial light modulators, and fast picosecond detectors to name a few. Some are actually not too difficult to fabricate, but they need sufficient impetus to spark interest among semiconductor device physicists...which is one of the objectives on this effort.

- Develop a high speed, low loss, and low cost fiber optic component
- Develop a high speed, low loss, and low cost fiber optic component
- Develop a high speed, low loss, and low cost fiber optic component

NEW COMPONENTS REQUIRED





NEW COMPONENTS REQUIRED

- Coherent fiber optic components (media, couplers, splices, modulators)
- Tunable sources and detectors – in large arrays (MQW)
- Monolithic femtosecond optic generating sources
- Fast planar 1D SLMs
- Low-repetition rate (<10GHz) real-time femtosecond detectors
- Optically controlled switches
- Optically controlled wavelength tuning
- Fast high-level protocol engines (>>Gbit/s TCP/IP)



SUMMARY

Optical protocols for networks provides a way of bypassing the electronic bottleneck and allowing speeds of 100 Gbit/s or more to be achieved. In principle, both stream and packet services can be conveyed over the same transmission fabric with no centralized control. The spectral CDMA technique described here provides the foundation for implementing basic boolean functions to build higher level network protocols such as arbitration, routing, and error detection. A natural by-product of the system is that it provides full non-blocking crossbar connectivity. Because the basic interface is all optical and switched at some sub-multiple of the actual channel, little electrical power is consumed by the network in the standby or active modes. As data rates increased, such a difference could become quite large.



SUMMARY

ADVANTAGES OF OPTICAL PROTOCOLS

- No electronics limit...
 - clock recovery independent of data format
 - synchronous or asynchronous operation
- Addressing, routing, encryption possible in the optical domain
- Crossbar connectivity
- Higher throughput efficiency (no one NIU limits aggregate capacity)
- Ideally suited for real-time stream traffic (voice, video, SAR)
- High security
 - difficult to tap by any direct optical methods
 - tapping is detectable at network receivers
 - movement of media is detectable during *power-off* periods
- Channel signalling rate limited by optical modulator to >20GHz